Observation of spontaneous quantum fluctuations in photon absorption by atoms

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Fluctuations in light absorption by atoms are observed by applying laser light on rubidium atoms and measuring the transmitted light intensity fluctuations. These fluctuations are spontaneous noise, which are generic to photon atom interactions. By making use of the sub-shot noise random signal detection technology, we have measured the spectra at sub-shot noise levels to reveal their rich nature, which had previously been unobserved. The effects of atoms transiting the laser beam, Rabi flopping in the optical transitions and Larmor precession of the magnetic moment are observed in the spectra. The properties of the fluctuations reflect not only the quantum behavior of atoms, but also that of light.

Quantum aspects of photons, atoms and their interactions have brought about new exciting phenomena, such as Bose Einstein condensation in gases[1], quantum teleportation[2], quantum key distribution[3] and recent developments in atomic clocks[4]. Most investigations into the properties of photon atom interactions make use of coherence of a large number of atoms to obtain their average properties. While this approach gives rise to relatively large signals which are measurable, it also averages out the quantum fluctuations intrinsic to the system. Spontaneous noise in the light transmitted through atomic vapor should contain all the information about the interactions between a single atom and photons, yet the nature of its spectrum is unknown. Here, we report on the measurements of this spectrum, which contain fluctuations that arise generically in photon atom interactions. The measured spectra reveal the effects of atoms transiting the laser beam, Rabi flopping and Larmor precession of the magnetic moment. The main reason these spectra had not previously been seen is that the size of the fluctuations in the transmitted light is small compared to the background (ratio $\sim 10^{-7}$ in our experiments) and the fluctuations are buried underneath the photon shot noise. Our measurements were made possible by statistically reducing the shot noise by four orders of magnitude through methods we developed. Additionally, the effects of the laser noise are reduced through stabilization and differential detection. The properties of the fluctuations reflect not only the quantum behavior of atoms, but also that of light. Measuring these fluctuations opens a way to direct measurements of quantum properties of photon atom interactions. Similarly to the thermal and shot noise that play important roles in current science, we expect the spontaneous noise arising from photon atom interactions to also play such a crucial role in the near future.

Our experimental principle is simple; we apply the minimal amount of external perturbation to measure spontaneous noise caused by photon atom interactions, just by shining light on atomic vapor. We further apply a static magnetic field, but only when studying its effects. In our experiment, a laser beam (power P, beam waist w), which has the resonant frequency for atomic transition levels is shone on sample cells containing rubidium (Rb) vapor. A large fraction of the beam traverses the cell and we measure the intensity of the transmitted beam using photodiodes, to find its fluctuations. We obtain the fluctuation spectrum after noise reduction, as described below. In this work, for clarity and simplicity, we restrict our attention to circularly polarized light in resonance with the ^{85}Rb D_2 transition from the hyperfine level $5^2\mathrm{S}_{1/2}(\mathrm{F}=3)$ to $5^3\mathrm{P}_{3/2}$[5]. We have further investigated fluctuations in different atomic level transitions and the effects of using light with linear polarization. The physics of the spectra in those cases can also be understood in a fashion similar to what is presented here.

In Fig. 1, a typical measured fluctuation spectrum in the transmitted light intensity is shown. Through systematic analyses of these types of fluctuation spectra, we have identified three kinds of physics that underlie this spectrum. A relatively broad peak below few hundred kHz is caused by the intensity changes due to atoms transiting the laser beam. We shall call this the transit noise. The distinct feature that exists from around 1 MHz to few times 10 MHz, which we call Rabi noise, is due to the Rabi flopping[6–8]. When the atoms are in the ground state, they absorb photons, reducing the transmitted light intensity and when they are in the excited state, they increase the transmission through stimulated emission. The atoms also decay spontaneously, giving rise to further random fluctuations in the intensity. The noise peak at 1.7 MHz occurs when a magnetic field is applied to the atoms, in addition to the circularly polarized laser beam. The atoms in the ground state perform Larmor precession under this magnetic field, causing the absorption coefficient to vary. Quantum mechanically, this noise arises due to the transitions between the Zeeman sublevels and hence is here called Zeeman noise. The behavior of these three types of spontaneous noise and their underlying physics is explained in more detail below. The shot noise level for this spectrum, $2eI$, is indicated in Fig. 1, where e is the electron charge and I the photocurrent. It can be seen from this that the analysis of these fluctuations is not possible without the elimination of the shot noise. Also for comparison, the spectrum for Rb vapor buffered with nitrogen at pressure 2.7×10^4 Pa, which has the same shot noise level, is shown in Fig. 1. In this case, the collision time scale is much shorter than the transit and Rabi flopping time scales, so that their corresponding spontaneous noise are drastically reduced.

We briefly explain the experimental scheme and the noise reduction we employ, which is necessary for obtaining the spectra in this work. The basic underlying scheme to measure the intensity fluctuations of the transmitted light is shown in Fig. 2(a). In this scheme, the intensity of the light transmitted through the cell is measured using a photodetector (PD). The resulting

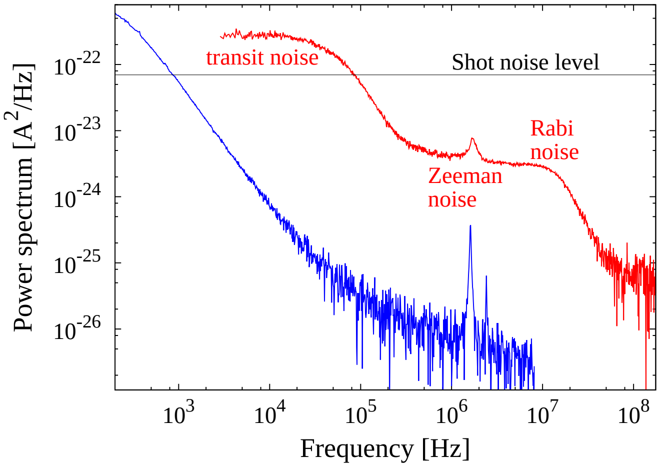

FIG. 1: (Color online) A typical measured spectrum of intensity fluctuations. The beam was transmitted through Rb gas, measured as photocurrent fluctuations ($P = 615\,\mu$W, $w = 0.96$ mm, red). Transit noise, Zeeman noise and Rabi noise are seen at progressively higher frequencies, respectively. A spontaneous noise spectrum for the buffered Rb gas whose fluctuations are much smaller is also shown ($P = 650\,\mu$W, $w = 0.53$ mm, blue). In this case, Zeeman noise for ^{87}Rb atoms is also visible since their transitions also occur, due to collisional broadening. The shot noise level (black), common to both spectra, is also indicated.

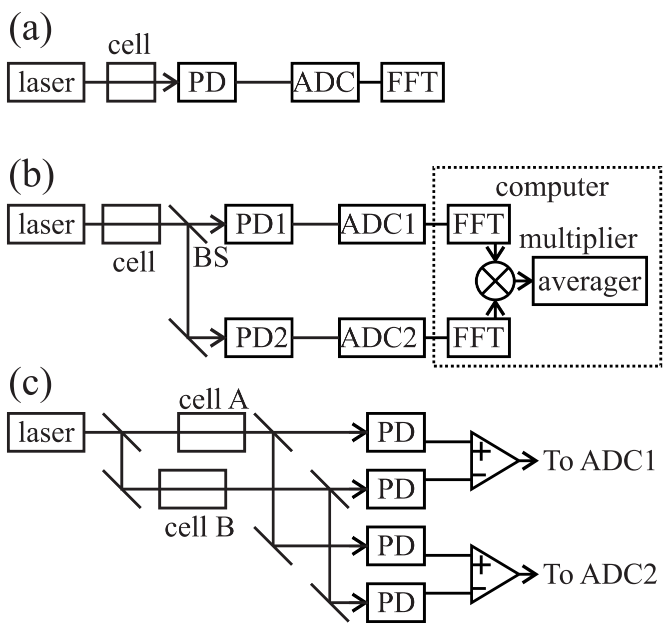

FIG. 2: The schematics of our measurement system: (a) A straightforward scheme for measuring intensity fluctuations of light passing through a gas cell that forms the basis of our setup. (b) A measurement system with shot noise reduction. (c) The measurement system used in this work, which incorporates differential detection in addition to the shot noise reduction. BS: Beam splitter. FFT: Fast Fourier transform.

photocurrent is digitized using an Analog-to-digital converter (ADC) and then Fourier transformed to obtain its fluctuation spectrum. This setup, however, is insufficient for obtaining spectra such as the one shown in Fig. 1, due to the unavoidable existence of extraneous noise. Any measurement includes various kinds of unwanted noise, of which shot noise and the signal induced by the laser noise are important in the current setup.

Shot noise inevitably occurs in any photoconversion and is often regarded as a limiting factor in the precision, "standard quantum limit", for these types of measurements[8]. Indeed, previous measurements of spontaneous noise made use of the small amount of Zeeman noise that could be seen above the shot noise level in Fig. 1[12–15]. In this work, for the first time, we have been able to observe what lies underneath this shot noise level, to uncover the transit and Rabi noise in addition to the Zeeman noise, and clarify their underlying physics. To accomplish this, we used multiple PD's (PD1,2) to make multiple simultaneous measurements $D_j = S + N_j$ $(j = 1, 2)$ of the spontaneous noise S (Fig. 2(b)). N_j is any *uncorrelated* noise that arises in each

PD, including the shot noise. We compute the averaged correlation of the Fourier transforms of the measurements $\tilde{D}_j$ $(j = 1, 2)$ to obtain the spontaneous noise spectrum,

$$\langle \overline{\tilde{D}_1} \tilde{D}_2 \rangle \longrightarrow \langle |\tilde{S}|^2 \rangle \qquad (\mathcal{N} \longrightarrow \infty) \quad . \tag{1}$$

Here, $\mathcal{N}$ is the number of averagings. $\langle \overline{\tilde{S}} \tilde{N}_j \rangle$ and $\langle \overline{\tilde{N}_1} \tilde{N}_2 \rangle$ average to zero, statistically, in the limit of infinite number of averagings. It is crucial here that the shot noise arising in different PD's are uncorrelated due to its quantum nature. In this work, we have achieved a reduction by four orders of magnitude. This method for achieving sub-shot noise in measurements has proven successful in obtaining surface thermal fluctuation spectra[9–11].

Another unwanted effect is the noise that occurs generically in a laser source, even with stabilization, especially at higher powers. This noise, through photon atom interactions, give rise to extraneous contributions to the spectra[13]. In the current experiment, the laser noise induced signal in the fluctuation spectra have been reduced to such a level to be negligible for smaller light powers even with the setups of Fig. 2(a),(b), yet substantial signal remains for larger powers in this case. To eliminate this signal, whose origin is laser noise, we employ two independent gas cells. The spontaneous noise in these two cells are independent, even though they are set up identically. On the other hand, the laser noise induced signals are caused by the same light source and are identical, so that they can be removed through differential detection. Incorporating this differential detection in addition to the shot noise reduction system described above, we arrive at the measurement system used in this work, shown in Fig. 2(c).

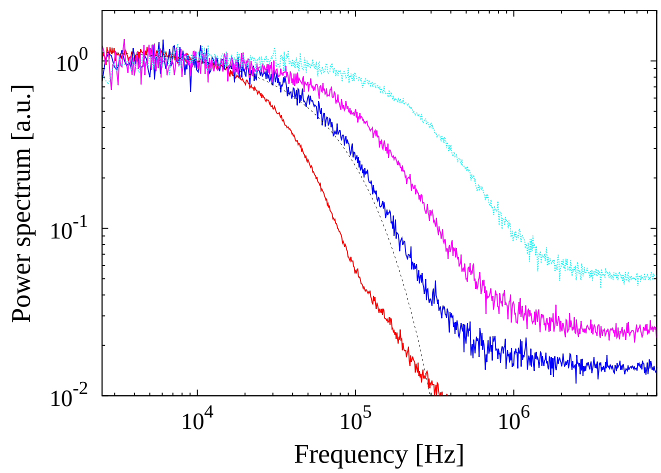

FIG. 3: (Color online) Transit noise spectra: Beam sizes are $w = 2.1$ (red), 0.64 (blue), 0.34 (magenta), 0.17 (cyan) mm and the corresponding fall off frequency increases in this order. Results from the theoretical calculation for $w = 0.64$ mm (black dashed) agrees reasonably well with the experimental results, but falls off at a slightly smaller frequency. Here, the spectra were normalized to make the fall off frequency difference clearer (a.u.: arbitrary units).

Semiconductor laser, DFB-0780-080, Sacher lasertechnik (wavelength 780 nm) was used as the light source. The spectral width of this source is about 3 MHz, the same order as the spectral width of Rb-D2 transitions, which is 6 MHz. We further narrowed the spectral width to less than 1 kHz with an optical feedback system using a confocal cavity (SA–300, Technical Optics)[16] and additional electrical feedback. Analog to digital conversion was performed by PicoScope5203 (ADC, 8bit,500Ms/s, PicoTechnology). Fourier transforms and averagings were computed on a personal computer. The data acquisition time is around 10 seconds, but the total measurement time is about five minutes, due to limitations in the data analysis speed. Rb atoms sealed in vacuum Pyrex glass cells were used as samples and were heated as necessary. Light source was circularly polarized using a 1/4 wavelength plate and a static magnetic field generated by a Helmholtz coil was applied, when required.

The transit noise spectra is shown for beams with various beam sizes in Fig. 3. Since the transit time scale varies as $1/w$, the fall off in the spectrum occurs at higher frequencies for smaller w. A rough estimate for this fall off frequency can be obtained as $2w/v_{2\mathrm{D}}$, where $v_{2\mathrm{D}}$ is the average thermal velocity in two dimensions. For $w = 1$ mm at 320 K, $2w/v_{2\mathrm{D}} \sim 8 \times 10^{-6}$ s, consistent with the results in Fig. 3. The theoretically computed spectrum is seen to agree well with the experimental results. There is a small deviation in the observed spectra from the theoretical spectra, shifting the transit noise spectra towards higher frequency. This can be understood as the results of two causes: An atom in the laser beam absorbs and emits photons, much like a two level system[8]. However, the atom can also spontaneously decay to a state which is not in resonance with the incoming light, depopulating this two level system. This effectively shortens the transit time, leading to a higher frequency for fall off in the transit noise spectrum. This suggests that the deviation should be larger for level transitions that are easier to depopulate,

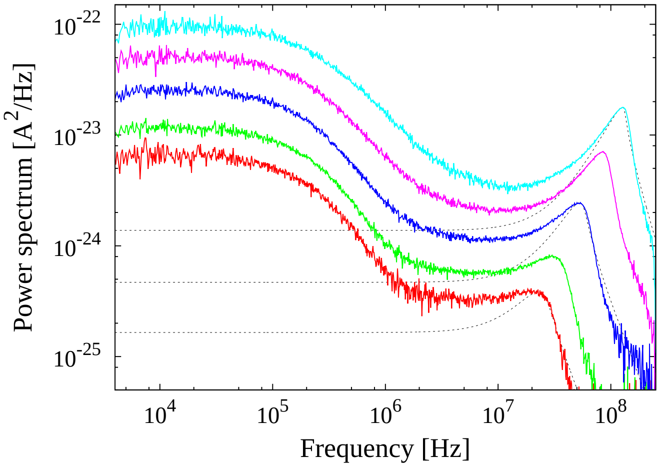

FIG. 4: (Color online) Dependence of the spectrum, in particular the Rabi noise, on the light power. $P = 57$(red), 96(green), 195(blue), 429(magenta), 870(cyan) μW, all for $w = 0.19$ mm. For larger P, the spectrum has a larger magnitude and the peak in the Rabi noise is at a higher frequency and sharper. Theoretical computations for the Rabi noise are shown (black dashed) for $P = 57,\ 195,\ 870\,\mu$W, which are consistent with the measurements.

which we have further experimentally confirmed. Another reason is that the absorption by atoms reduce the light intensity, modifying the beam profile and effectively shortening the transit time. Apart from the overall magnitude, the shape of the transit noise spectrum is experimentally seen to depend only weakly on P, as is also evident in Fig. 4.

The spectra for different laser powers are shown in Fig. 4, for the same beam size. Zeeman noise is not present since no static magnetic field has been applied. Rabi noise develops a pronounced peak for higher laser powers and the peak frequency increases with the laser power. The peak frequency is around the Rabi frequency, $\mu E/h$, though the full behavior is more complex. Here, μ is the dipole moment of the atom, E is the maximum electric field strength and h is the Planck's constant. The peaks have widths mainly for three reasons: First, the electric field strength within the laser beam depends on the location. Second, the atoms have thermally distributed velocities, detuning the light frequencies through Doppler shifts. Third, apart from Rabi flopping, the atoms can spontaneously decay, contributing to a finite width. The theoretical prediction including all these aspects has been computed and shown in Fig. 4 and is seen to agree well with the measured spectrum. The spectrum manifests the quantum properties of the underlying quantum field correlations, which can be obtained using the quantum regression theorem[7, 8, 17]. Semi-classical approximation, such as applying the Bloch equations, does not suffice here, since if we treat photons classically, the quantum fluctuations intrinsic to the field correlations are averaged out. Therefore, not only the quantum properties of the atom, but also the quantum properties of photons are reflected in the spectra.

In Fig. 5, static uniform magnetic fields with different strength are applied to the atoms, with other conditions fixed. As the magnetic fields become stronger, we see that the Rabi noise is suppressed and the peaks in Zeeman noise become more pronounced. The peak frequencies are well described by μB, where μ is the magnetic moment of the ^{85}Rb atom and B is the magnetic field. Peaks at frequencies $2\mu B$ are also clearly visible. It is important to note that in these measurements, only a static magnetic field and a single laser beam is applied, with no additional external perturbations driving the system away from equilibrium. The observation of Zeeman effect in spontaneous noise has previously been attempted[12, 13] and seen[14, 15]. However, the shot noise reduction was not applied there so that the the Zeeman noise signals were not much above the shot noise level. In our experiment, we obtained Zeeman noise with high contrast, by averaging out the shot noise. The spectra obtained in this work further revealed the transit and Rabi noise within, whose mechanism could be understood. While outside the scope of this work, the clear signals due to Zeeman noise have allowed us to measure power broadening and light shifts in the Zeeman frequency[18, 19].

In this work, measurements of spontaneous noise spectra required no external perturbation except for those essential to the noise itself. We have been able to reveal the structure of the spectrum below the shot noise level, which had previously been unseen. The basic aspects of quantum physics underlying this structure were then elucidated. We expect these spectra to provide an ideal laboratory for studying various quantum properties of photon atom interactions, with precision and without ambiguity.

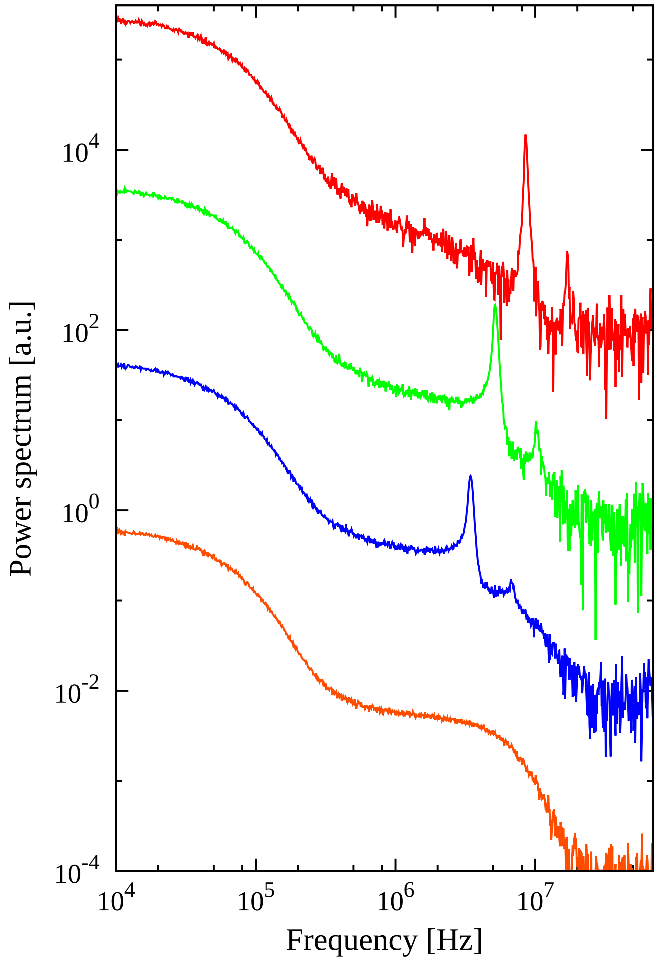

FIG. 5: Spectra with Zeeman noise under static magnetic fields. Magnetic field strengths are $B = 0$(orange), $2B_0$(blue), $3B_0$(green), $5B_0$(red) with $B_0 = 3.4\,$G from bottom to top. Spectra for $B = 2B_0, 3B_0, 5B_0$ were rescaled by factors of $10^2, 10^4, 10^6$ respectively, to clearly separate the plots. $P = 137\,\mu$W, $w =$0.96 mm.

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